Variable Stars in the Large Magellanic Cloud: Discovery of Extragalactic W UMa Binaries[1]

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ABSTRACT

We observed a field in the disk of the LMC on two consecutive nights in search of rapid variable stars. We have found two pulsating stars of type RRab and δ Sct, and four binary stars, among the latter one sdB or CV below the LMC blue Main Sequence and three very close binary systems on the MS. At least one of the MS binaries, and possibly all three, are the first solar-type (W UMa-type) contact binaries to be detected in any extragalactic system and observed to obey the same $M_V = M_V(\log P, B-V)$ calibration as the Galactic systems. Given the selection effects due to small amplitudes at faint magnitudes, the frequency of such binaries in the disk of the LMC with its large spread in population ages is not inconsistent with that in the disk of our Galaxy, and contrasts with the lack of binaries found in earlier observations of the much younger LMC cluster LW55.

Subject headings: galaxies: individual: (Large Magellanic Cloud) – – galaxies: star clusters – Magellanic Clouds – stars: binary – techniques: photometric

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[1]Based on the data obtained at Las Campanas Observatory, operated by the Carnegie Institution of Washington, during the University of Toronto time allocation.

1. INTRODUCTION

Very little is known about short time scale (< 1 day) variability of stars in the Magellanic Clouds. Only recently, the availability of large telescopes located at excellent sites has made it possible to consider time-domain monitoring of the stellar population at brightness levels reaching and beyond the levels of the Turn-Off Point of the oldest stellar population in LMC at $V \simeq 20.5$.

The current study addresses the detection and characterization of contact binary stars in a typical LMC field 1.7 degrees from the center of the LMC. This field was selected taking guidance from an HST study of the stellar population in the LMC (Smecker-Hane et al. 2002), where it was called Disk-1. Availability of the archival HST images was one of the reasons for this study as it permitted us to check for stellar blends and assure better consistency of our results. The field is characterized by a constant star formation rate from the advanced age of 7.5 to 15 Gyr until recently. In a companion study on short time-scale variability in the LMC (Kaluzny & Rucinski 2003), the studied field was dominated by a population of the open cluster LW55 with an age of about 1.5 Gyr, in the presence of an underlying older population with an age about 4 Gyr or more. We did not find any short-period binaries in or around LW55, but only several short-period pulsating stars instead.

We present the observations and show the color – magnitude diagram for stars in the field in Section 2. The results of the search for short-period variable stars are given in Section 3. Section 4 concludes the paper and summarizes the results.

2. Observations

2.1. Instruments and observing conditions

We used the Magellan/Baade 6.5m telescope with the TEK5 CCD $2K \times 2K$ camera which had a focal scale of 0.069 arcsec/pixel. The field of view was 137×137 arcsec square. The images were binned by 2 pixels in both directions before extraction of photometry, with the resulting scale of 0.138 arcsec/pixel. The median seeing during our run was 0.94 arcsec in the V filter and 1.09 arcsec in the B filter. The binned images significantly oversampled the Point Spread Function (PSF) even in the cases of the best seeing. The search for variability was done mainly with the V filter (47 images) but also with the B filter (12 images). All V-filter exposures were 600 s while all B-filter ones were 900 s.

The observations were made on two nights, 2002 January 4/5 and 5/6. We conducted 6.2 hours of variability monitoring on the first night and 7.3 hours on the second night. The nights can be characterized as gray time, with the fraction of the illuminated area of the Moon disc of 61% and 50%, respectively.

The image processing was identical to that described in Kaluzny & Rucinski (2003). The initial

processing of the images was done with standard procedures from IRAF[2] with a combination of the dome and sky flats used for the CCD response flat-field corrections.

The astrometric calibration was based on 48 reference stars from the USNO-B catalogue (Monet et al. 2003). The random errors for the calibration do not exceed 0.5 arcsec, based on the recovered coordinates of the USNO-B stars.

2.2. The field Disk-1

Figure 1 shows the sky image in the pixel space (after the 2×2 binning), with pixels 0.138 arcsec in size and with a total field of view of 2.3×2.3 arcmin square. The field in Figure 1 is oriented with East to left and North down. The X-coordinate runs W to E, while the Y-coordinate runs N to S.

2.3. Photometric calibration

The photometric calibrations were done using three of Stetson's standard star fields (Stetson 2000): 2 stars in NGC 1866, 6 stars in E4–108 and 15 stars in NGC 2682 (M67). The fields were observed with air masses ranging from 1.13 to 1.77. The extinction coefficients as well as the color terms and zero points of the transformations from the instrumental to the standard BV system were determined from observations of all 23 standards stars. The adopted formulae were:

$$
\begin{aligned}
v &= V - 1.050 + 0.021 \times (B - V) + 0.089 \times (X - 1.25) \\
b &= B - 0.702 - 0.142 \times (B - V) + 0.147 \times (X - 1.25)
\end{aligned}
$$

X is an air-mass and lower-case symbols denote instrumental magnitudes derived with the aperture photometry with the DAOPHOT program (Stetson 1987). Figure 2 shows transformation residuals for the standard stars.

Table 1 contains the results of our photometry for 4413 stars in the same pixel coordinate system of as shown in Figure 1. The reference frames in V and B were obtained by collation of, respectively, 10 and 7 individual frames with the best seeing, in the way as described in detail in Mochejska et al. (2002). The seeing in the reference images had FWHM of 0.62 arcsec in V and 0.74 arcsec in B. The quoted errors in Table 1 do not reflect stellar variability but are just the internal errors of the PSF photometry on the reference images.

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[2]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF

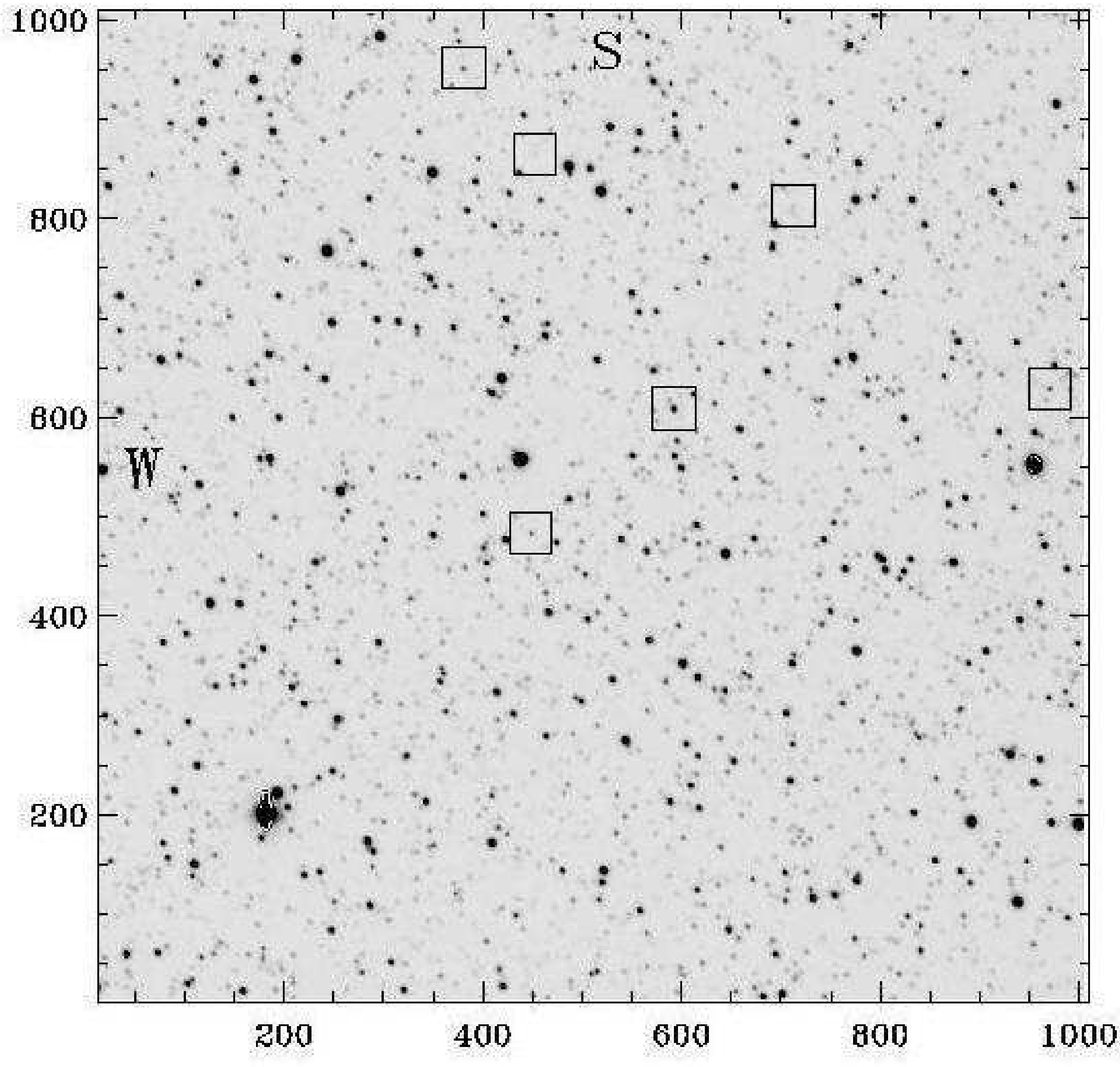

Fig. 1.— The chart of the field in the pixel coordinates, the same as in Table 1. The variable stars can be found using the boxes marked in the figure, the X, Y coordinates given in Table 2 and the individual charts in Figure 8.

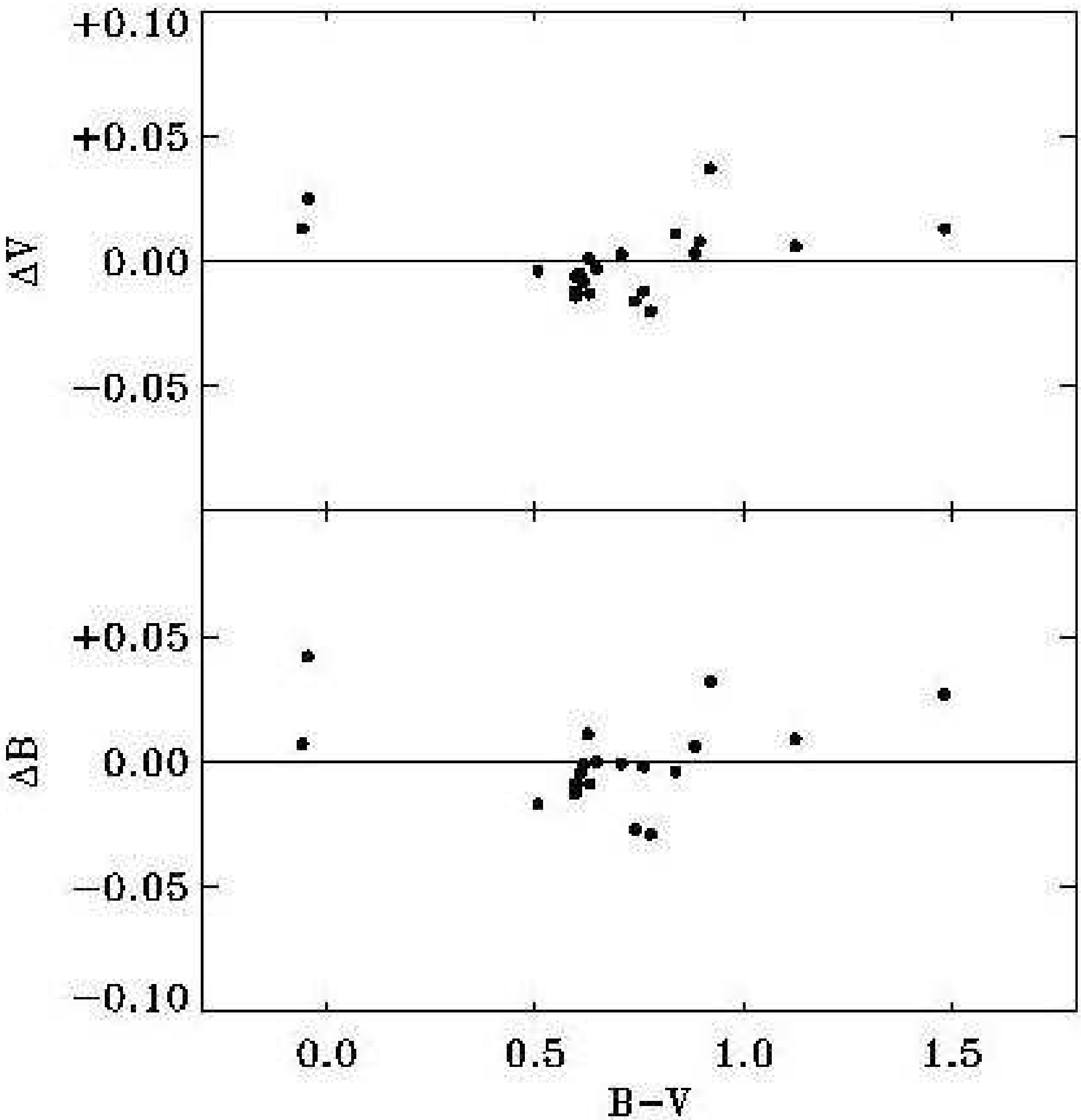

Fig. 2.— Residuals for our photometry of the standard stars, in the sense 'our minus standard" for V and B magnitudes.

2.4. Photometric uncertainties

It is difficult to assess reliably errors of single-frame profile photometry in a crowded field such as Disk-1. Some formal errors, such as those returned by the DAOPHOT software, are often too optimistic as they tend to miss problems related to blending.

We were not able to compare directly our results with those of Smecker-Hane et al. (2002) which were discussed only in graphical and verbal form. However, we have analyzed the archival HST–WFPC2 data: V: 2 × 500s, F555W, #u4b10905r and #u4b10906r; I: 2 × 300s, F814W, #u4b10902r and #u4b10904r; the pairs of images were used to remove cosmic rays. We estimated deviations between our photometry and the HST photometry, the latter obtained using the "HSTphot" software package (Dolphin 2000a,b). While no obvious trends exist in the V magnitude differences for 963 common stars in the range $18 < V < 25$, there does exist an offset of $\Delta V = -0.08 \pm 0.02$ (our results brighter). This offset has not been applied to the photometric results listed in Tables 1 and the variable stars (Section 3). We note that systematic uncertainties in the WFPC2 photometry are estimated at about 0.05 mag., and may even reach 0.1 mag. (Piotto et al. 2002).

To estimate random uncertainties, we compared our results with the HST results for individual stars. The deviations for the sample of 963 common stars are shown in Figure 3. After accounting for the systematic shift of −0.08, binning the deviations in one magnitude intervals, and with an assumption that errors from both sources add quadratically, we estimate the *rms* scatter at $\sigma V \simeq 0.02 - 0.04$ for for $V < 21$; it increases to 0.09 at $V = 22$ and to 0.11 at $V = 23$.

Much more reliable than the above estimates are estimates of errors in the search for variable stars, obtained by comparison a large number of images analyzed using the image differencing technique. They are discussed in Section 3 in a discussion of amplitudes of detectable variable stars.

2.5. The color magnitude diagram

The photometric results for the whole field are plotted on the color–magnitude diagram (CMD) in Figure 4. As discussed by Smecker-Hane et al. (2002), the Disk-1 field contains populations of different age with clear indications that the star formation rate in this part of the LMC was constant over a long time. We can see the red horizontal branch (at about $V \simeq 19.5$) and the Main Sequence turn-off point (at about $V \simeq 21$) of the old population as well as a sequence of young stars extending to $V \simeq 18$.

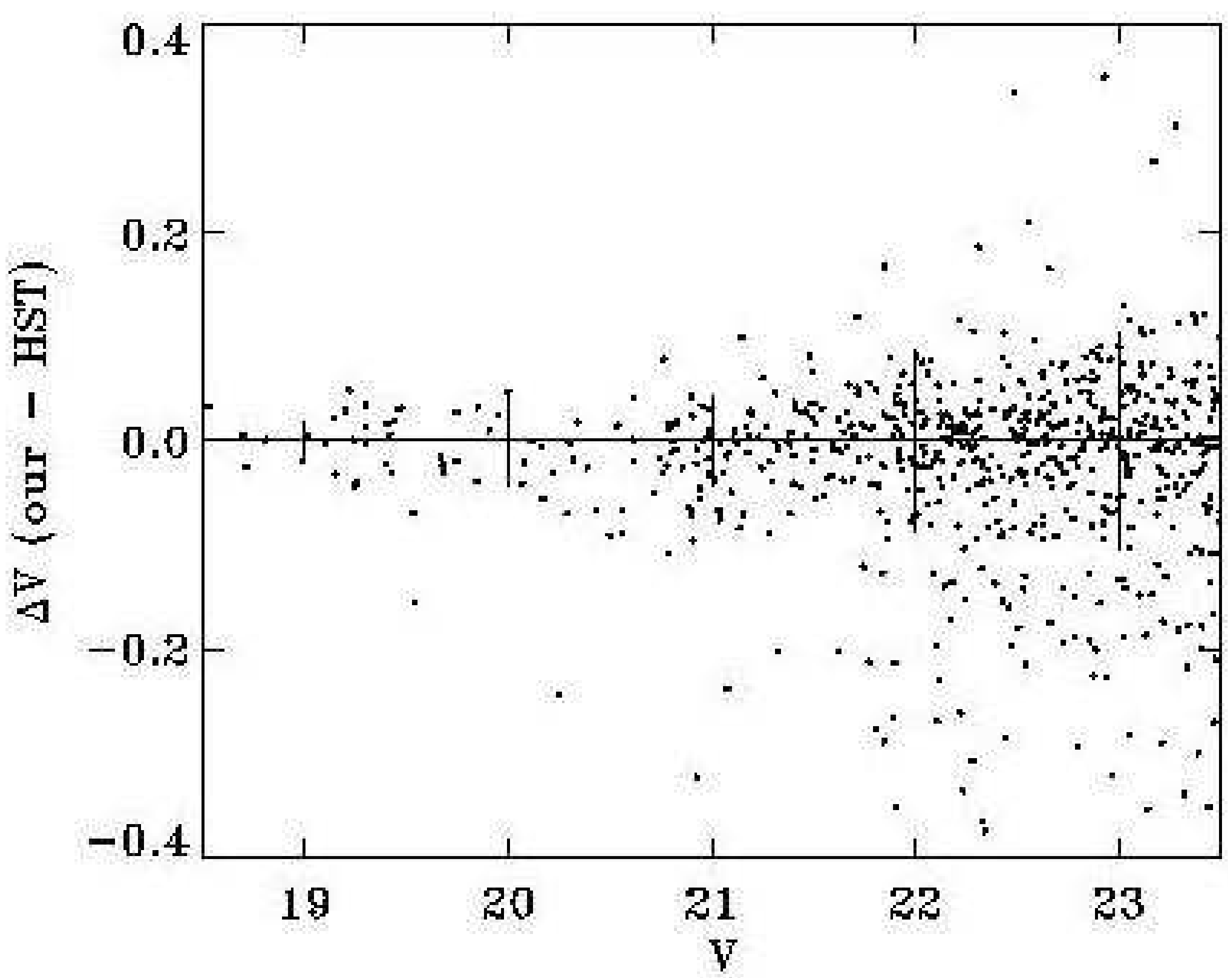

Fig. 3.— ΔV differences between our photometry and HST photometry (after allowance for the offset of -0.08 mag) can be taken as a measure of random errors at different magnitude levels. Estimates of the *rms* errors at one magnitude intervals are shown by vertical bars.

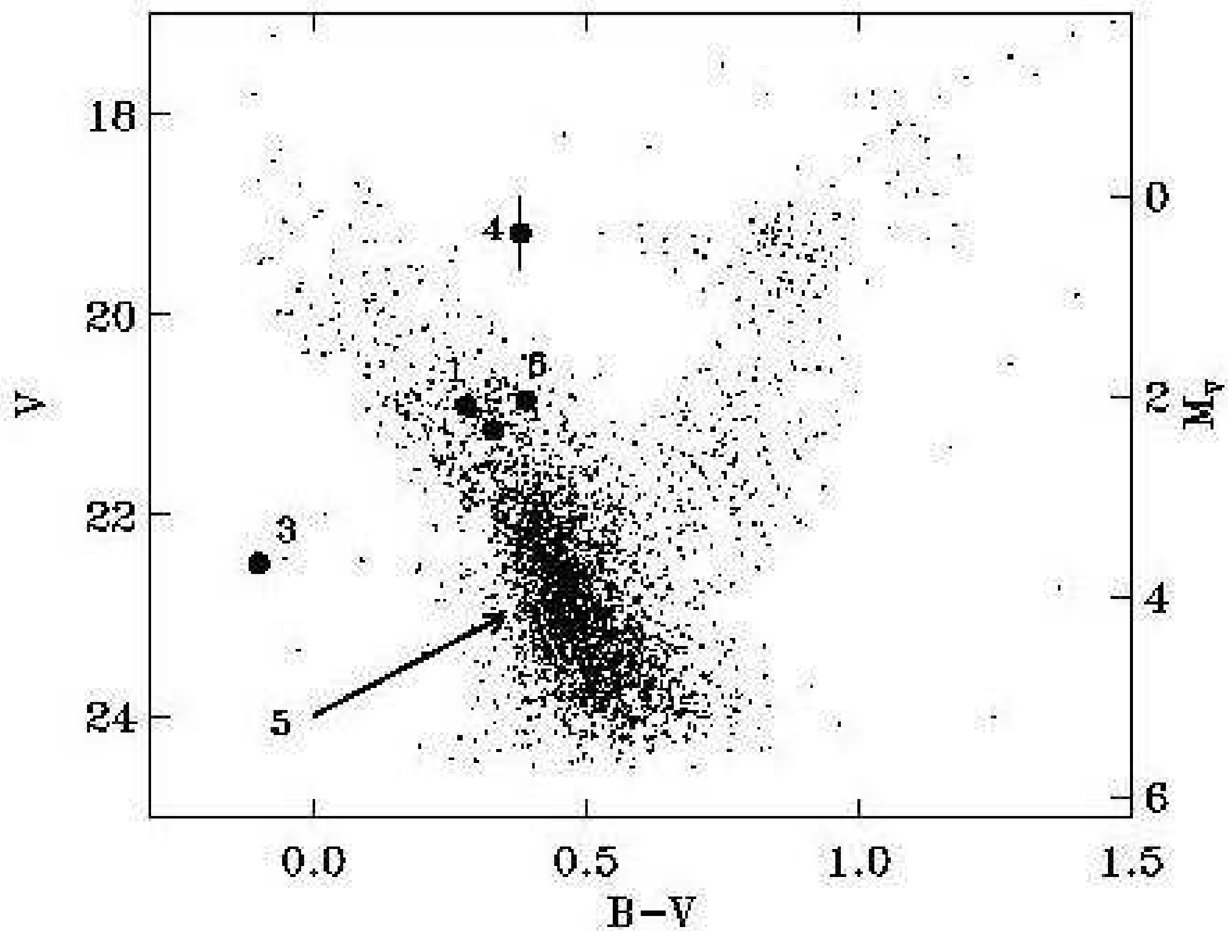

Fig. 4.— The CMD for the Disk-1 field. The six variable stars are marked with large filled circles at their median magnitudes and color indices. The vertical bar for V4 shows its observed ranges of variability in V; for the remaining variables the ranges are smaller than the symbol size. The absolute magnitude scale on the right vertical axis is based on the assumption of $(m - M)_0 = 18.5$ and $E_{B-V} = 0.10$.

3. Variable stars in Disk-1

3.1. Techniques and errors

A search for potential variable stars in the field Disk-1 was performed with the image subtraction package ISIS V2.1 (Alard & Lupton 1998; Alard 2000). Two methods were used to detect potential variable objects. First, we applied procedures which are included in the ISIS package and which are based on analysis of residual images. The second method relies on extraction – still within the ISIS package – of light curves for all stellar objects whose positions had been determined on template images with DAOPHOT/Allstar (Stetson 1987). Extracted light curves are subsequently examined for the presence of any possible periodic variations with a suite of programs based on the "AoV" algorithm (Schwarzenberg-Czerny 1997).

Figure 5 shows the *rms* versus the magnitude diagram for 6243 stars whose light curves were analyzed (this number is by about one half larger than the number of stars that went into the CMD). The *rms* errors were derived after rejection of the two most extreme maximal and minimal data points from data for each star. Not all points with large σ in the figure correspond to physical variables as automatic processing led to inclusion of a few easily identifiable stars with poor photometry, mostly in the extended wings of over-exposed bright stars. The figure suggests that assuming a $5 \times \sigma$ detection threshold, we should be able to detect variable stars with peak-to-peak amplitudes of $\Delta V \simeq 0.05$ at $V = 21.5$ and $\Delta V \simeq 0.10$ at $V = 22.5$. It is encouraging to note that the data were taken during gray time. Clearly, even during gray time, one may use the Baade telescope to look for variable stars in the LMC beyond the turnoff region at $V \simeq 22$.

3.2. Results of the variable star search

We have detected six variable stars in the Disk-1 field. They are marked on the color-magnitude diagram of the field in Figure 4 and are listed in Table 2, where their CMD numbers, X, Y and equatorial J2000 coordinates, the maximum and minimum V and median values of $(B - V)$ are given. The listed values of $(B - V)$ are uncertain because of the non-simultaneous nature of our B and V observations and because the exposure times were rather long (15 minutes in B). The $B - V$ data given in Table 2 are slightly different than the ones in Table 1 due to stellar variability along with differences in how the mean photometric values were determined.

The light curves of the variables[3] are shown in Figures 6 and 7, while the finding charts in pixel coordinates of Figure 1 are shown in Figure 8. Figures 6 and 7 give the V and $B - V$ curves,

[3]The tables of individual V and B magnitudes and interpolated $B - V$ are available from: http://astro.utoronto.ca/rucinski/LMC-Disk1/Var*_Disk1.dat

Table 1. Photometric data for LMC Disk-1

#	X	Y	RA[deg]	Dec[deg]	V	σV	$(B-V)$	$\sigma(B-V)$
1	16.43	841.77	77.92661	−71.19987	22.409	0.019	0.580	0.031
2	16.95	736.51	77.92596	−71.19575	22.363	0.008	0.339	0.016
3	17.06	175.30	77.92218	−71.17359	22.357	0.006	0.350	0.012
4	17.85	548.81	77.92495	−71.18848	17.787	0.004	0.831	0.008
5	17.86	423.94	77.92420	−71.18362	22.716	0.008	0.498	0.017
6	18.43	1002.93	77.92822	−71.20638	21.848	0.035	0.399	0.056
7	18.73	760.67	77.92633	−71.19669	22.535	0.007	0.429	0.013
8	18.87	461.99	77.92456	−71.18511	21.001	0.004	0.172	0.008
9	19.23	88.02	77.92155	−71.16988	23.817	0.015	0.533	0.037
10	19.99	662.28	77.92588	−71.19287	23.804	0.021	0.494	0.041
11	20.07	56.83	77.92130	−71.16853	21.416	0.007	0.389	0.016
12	20.12	488.31	77.92488	−71.18614	22.957	0.008	0.435	0.016

Note. — Table 1 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. The stars positions are given in the pixel X and Y coordinates of the reference image, as in Figure 1, and in the equatorial coordinates in the J2000 system. The formal errors given here can be used to compare relative uncertainties; the external estimates of the errors are discussed in the text.

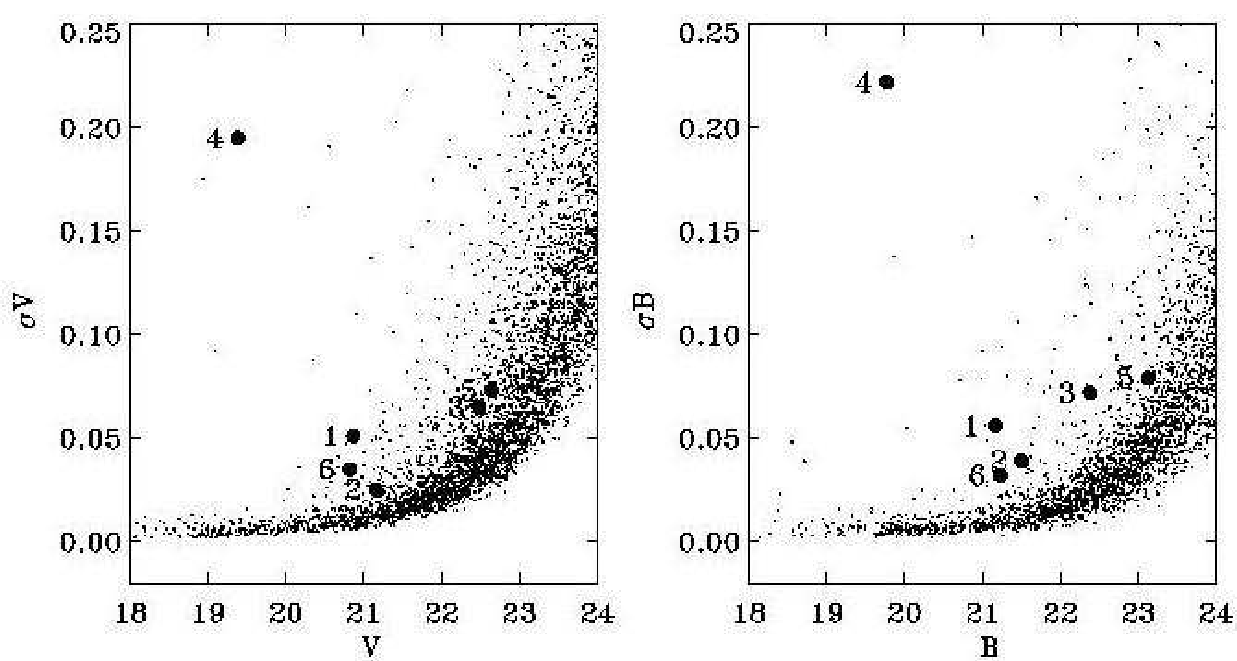

Fig. 5.— The *rms* errors of photometry based on the inter-comparison of the individual images used for detection of variability. The two panels show separately photometric errors in V and B bands versus the respective magnitudes.

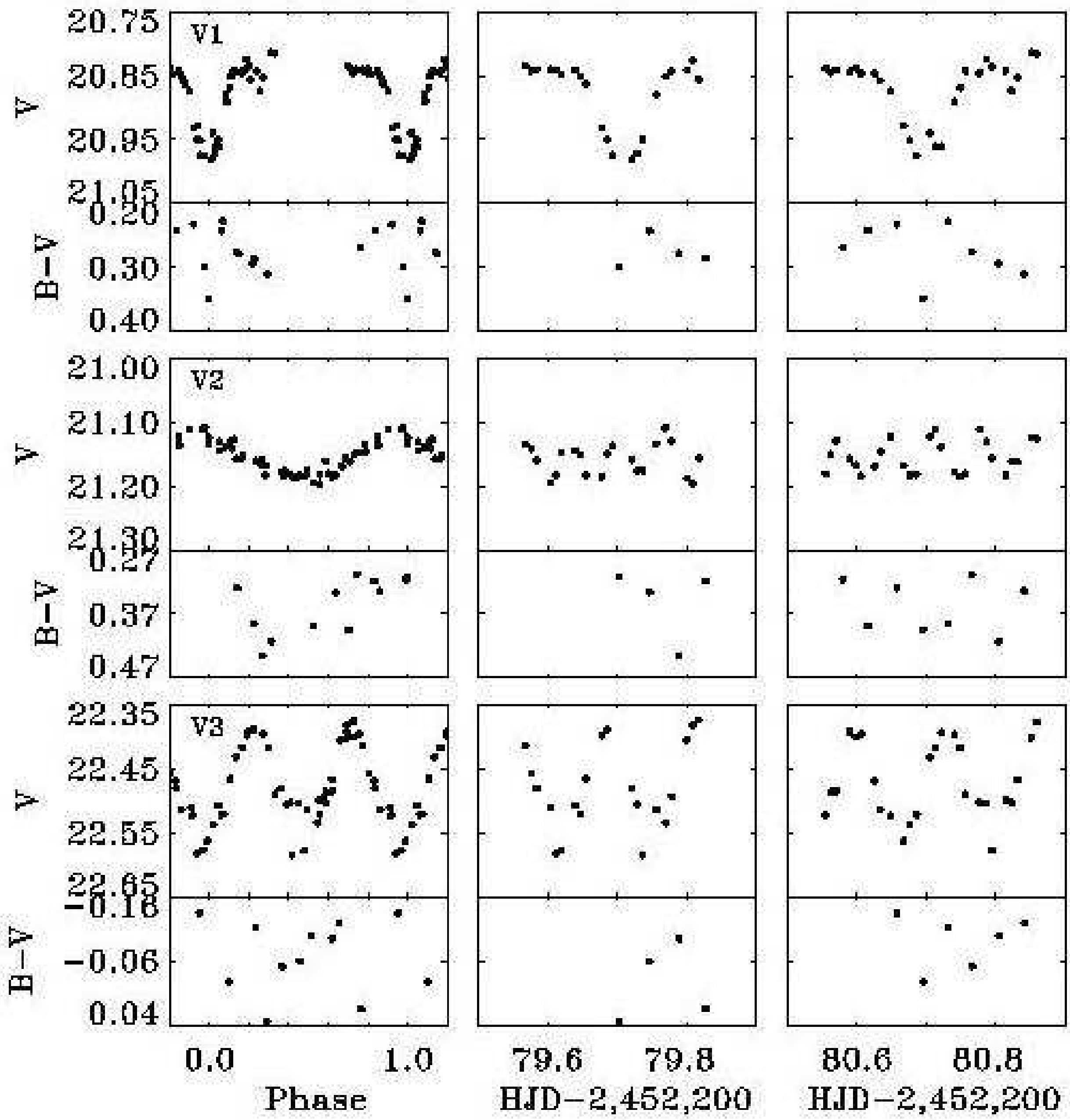

Fig. 6.— The light and color index curves for variables V1 – V3. For each star, the left panel shows the phased data with T_0 and the period as given in Table 2, while the two right panels show the individual nightly data. The vertical scale has the same range of $\Delta V = 0.3$ and $\Delta(B-V)$ for all stars, but the magnitude and color index levels are different.

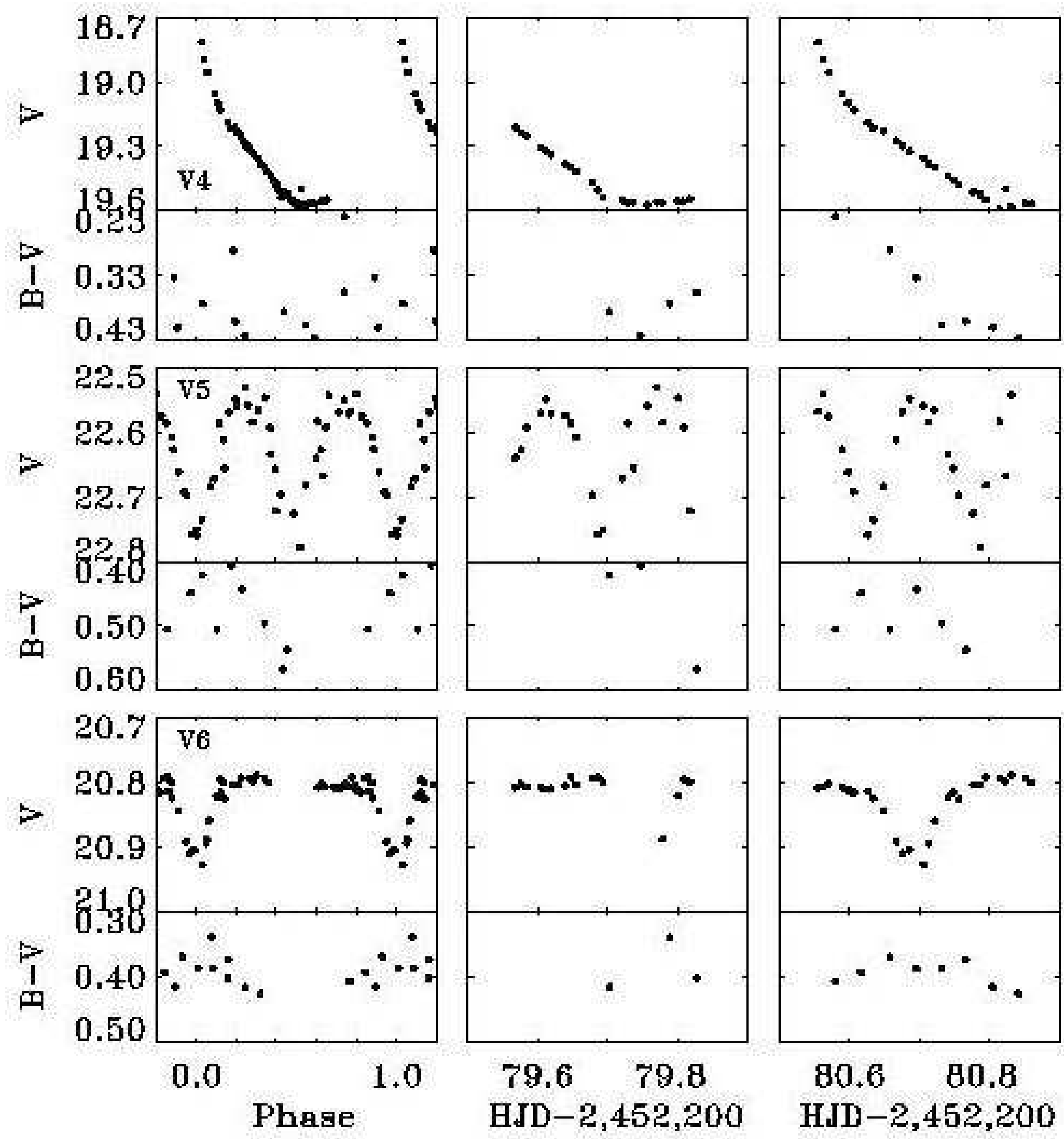

Fig. 7.— The same as in Figure 6, but for the variables V4 – V6. Note that for V4, the magnitude scale is expanded 3 times relative to that for the remaining stars.

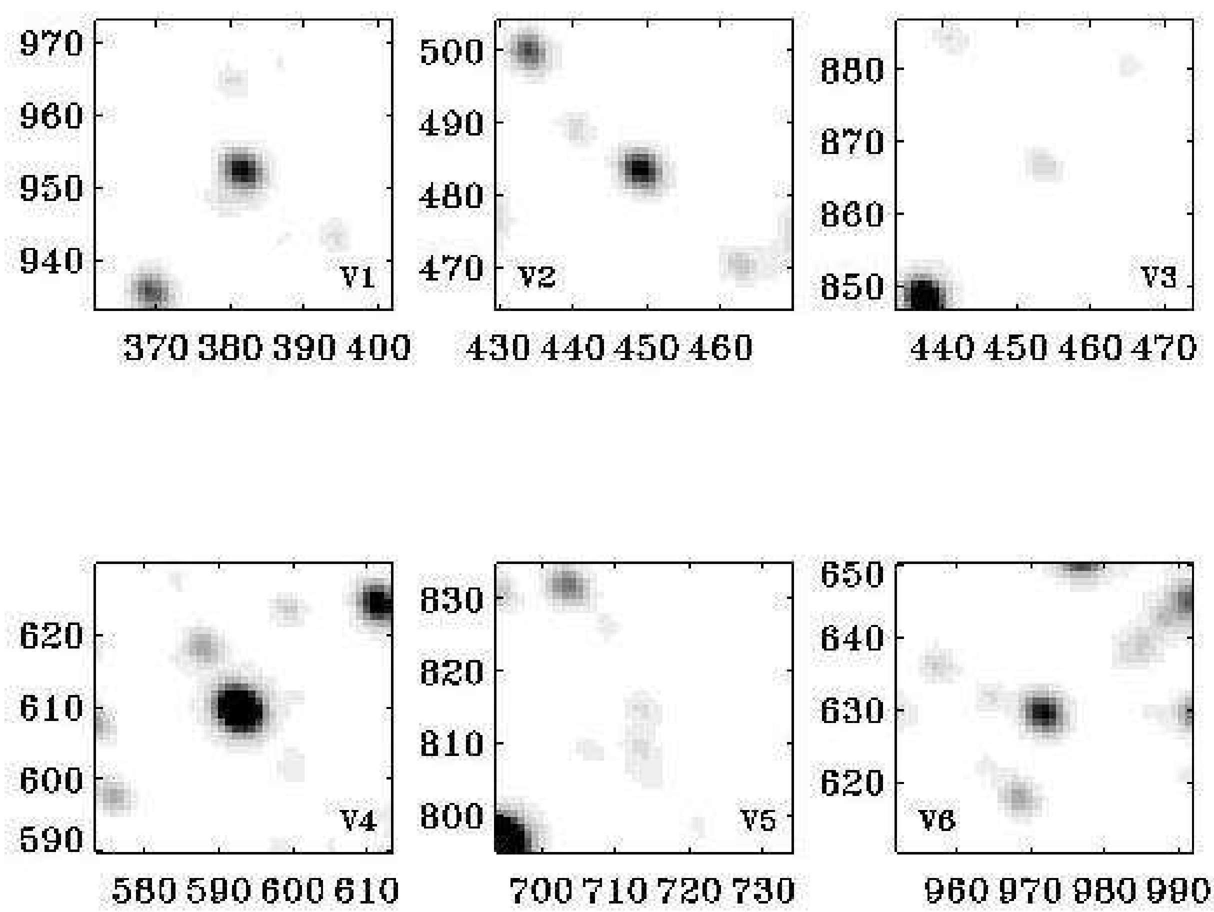

Fig. 8.— The finding charts of the variable stars showing 40×40 pixels of our reference image (Figure 1) centered on each of the variable stars.

the latter for the interpolated moments of the B observations. We do not discuss the B magnitude light curves in this paper because of their low precision.

We inspected the archival WFPC2 images (particularly the image WFPC2ASN U4B10905B) and found that all our detected variables are free from blending. We also found that our RA/Dec coordinates of the variables agree with the WCS of the WFPC2 image to 0.6 arcsec.

Obviously, due to the short duration of the program, we could detect only short time scale variables. On the other hand, we could probe relatively deeply and could detect variables among stars of very moderate brightness reaching as far down the main sequence as solar stars, in the LMC at $V \simeq 22 - 23$. The limited scope of the project is fully confirmed by the characteristics of the detected variables: As we can see in Fig. 4, four of the stars are located in the Main Sequence of the LMC; these are V1, V2, V5, V6. One of them, V2, is a δ Scuti variable, while the remaining ones are short period binary systems. V1, V2 and V6 are located in the turn-off region of the old population Main Sequence within $+0.28 < B - V < +0.39$ and $V \simeq 21$. We also detected one RR Lyr-type (RRab) variable and one very blue variable below the Main Sequence. We comment on the individual objects below.

- V1 (#1662) – A short period eclipsing binary with an amplitude of light variations of $\Delta V \simeq 0.15$, period $P = 0.49$ d and $B - V = 0.28$. Although the light curve may suggest a close, but detached binary, $M_V = 2.0$ predicted from $(m - M)_0 = 18.5$ and $E_{B-V} = 0.1$ perfectly agrees with the contact-binary calibration of Rucinski & Duerbeck (1997)(see also Rucinski (2000)), $M_V(cal) = 2.0$.

- V2 (#1984) – A short-period (0.0675 d) δ Sct or SX Phe pulsating star with $\Delta V = 0.06$ at $V = 21.15$. The light curve is relatively well defined thanks to the folding of several periods.

- V3(#1999) – An interesting blue star well below the Main Sequence at $V \simeq 22.45$ and $B-V \simeq -0.1$ (independent photometry on the reference image of Section 2.5 gives $B - V \simeq -0.05$). Variability is rapid; if it is a binary, as individual nightly observations suggest, then the period is 0.2607 day, but the period may be actually 1/2 of this value. We verified that the blue color of the star is not due to blending, which is possible in such a crowded field as Disk-1 because the archival WFPC2/HST images mentioned above clearly show that V3 is indeed very blue. The observed luminosity of V3 is consistent with a relatively bright Cataclysmic Variable in the LMC. The variable is isolated and bright enough that low-resolution spectra could be obtained from the ground.

- V4 (#2618) – This is an RRab pulsating star with well defined light variations, but an incomplete light curve. We assumed that two cycles elapsed between the two nights, P=0.538 d. Since we have not captured the light maximum, we have been unable to determine the initial (maximum light) epoch T_0 for this star; the maximum brightness is possibly above $V = 18.8$. Because the light curve is incomplete, we cannot relate photometric properties of the star to the horizontal branch of the LMC, but the properties are certainly consistent.

- V5 (#3175) – A rather typical contact binary well within the Main Sequence of the LMC, some +2 magnitudes below the Turn-Off Point, at $V_{max} = 22.57$. Assuming $B - V = 0.47$, $E_{B-V} = 0.1$ and $P = 0.3108$ d, the calibration of Rucinski & Duerbeck (1997) predicts $M_V(cal) = 3.5$; directly, with $(m - M)_0 = 18.5$, one obtains $M_V = 3.8$. This is consistent within the current uncertainties. V5 is the first certain W UMa-type binary identified in other galaxy.

- V6 (#4284) – A close eclipsing binary with $V_{max} \simeq 20.8$, $B - V = 0.39$ and the period of 0.469 d (assuming the observations cover two cycles). From the distance modulus, $M_V = 2.0$, while – assuming that the binary is really a contact one – the calibration of Rucinski & Duerbeck (1997) gives $M_V(cal) = 2.4$; the light curve does not look like that of a contact binary, however.

4. Summary and conclusions

We have photometrically observed a region of the Large Magellanic Cloud – called "Disk-1" by Smecker-Hane et al. (2002) – on two consecutive nights in search of short time scale variable stars. The time monitoring led to the discovery of four short-period eclipsing binaries and of two pulsating stars (RRab and δ Sct). The results clearly show that solar-type stars are accessible for such monitoring in the LMC down to $V \simeq 22.5 - 23$.

It appears to be significant that the field Disk-1 contains short period binaries. We discovered four such binaries, in contrast to the results for the LMC field of LW55 (Kaluzny & Rucinski 2003) which was observed in a practically identical way and where we detected only very low amplitude, pulsating variables of δ Scuti, SX Phoenicis or γ Doradus type, and no binaries. While small-number statistical fluctuation is still a possibility, the reason may be in the uniform distribution of stellar ages in the Disk-1 field (Smecker-Hane et al. 2002), contrasted with the population dominated by LW55 itself with an age of 1.5 Gyr.

Obviously, the number of short-period binaries is still small, 4 among 6243 monitored including possibly 3 contact binaries, compared with the Galactic field where typically one among 500 FGK dwarfs is expected to be a contact binary (Rucinski 2002). However, all binaries detected by us have moderately large amplitudes, $\Delta V > 0.1 - 0.15$, which may result from selection effects operating at the faint levels of $V \simeq 24$ in a very crowded field; we simply could not detect low amplitude binaries. Numbers of close binaries apparently increase rapidly with decreasing amplitude of light variations (Rucinski 2001). This is confirmed by the complete ($\Delta V > 0.05$) sample of bright, short-period binaries in the solar neighbourhood, mostly from the Hipparcos catalog, with $V < 7.5$ (Rucinski 2002). In this sample, only about 1/3 of all binaries have amplitudes $\Delta V > 0.10$ and almost 1/2 of them have amplitudes $\Delta V < 0.15$. Taking this amplitude selection effect into account, the discrepancy between the observed 3 and the expected 8 contact binaries does not appear to be significant, assuming that about 2/3 of the monitored stars were FGK dwarfs.

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Table 2. Variable stars in Disk-1

V	#	X	Y	V_{max}	V_{min}	$(B-V)$	RA(hh:mm:ss)	Dec(dd:mm:ss)	Type	Period(d)	T_0
1	1662	381.82	953.11	20.84	20.97	0.28	5:11:53.10	−71:12:14.6	EA/EW:	0.491(1):	79.715
2	1984	449.61	484.19	21.12	21.18	0.33	5:11:54.51	−71:11:09.4	δ Sct	0.0675(1)	79.568
3	1999	453.81	866.78	22.39	22.57	−0.10	5:11:55.02	−71:12:02.0	sdB/CV	0.2607(2)	80.67
4	2618	593.36	609.87	<18.80	19.56	0.38	5:11:58.71	−71:11:25.8	RRab	0.538:	
5	3175	713.90	814.92	22.57	22.78	0.47	5:12:02.35	−71:11:53.2	EW	0.3108(1)	80.625
6	4284	971.90	630.27	20.79	20.91	0.39	5:12:09.52	−71:11:26.2	EA/EW:	0.469(1):	80.69

Note. — The variable star numbers, as used in the text, are given in the first column, while identifications in Table 1 are in the second column. The full names which conform to the International Astronomical Union recommendations are “Disk1–LCO–V...”. The J2000 equatorial coordinates were obtained through an astrometric frame solution using positions of 48 stars from the USNO-B catalogue; this solution reproduces the J2000 coordinates of these stars with residuals not exceeding 0.5 arcsec in RA and Dec. Note that the V and $B-V$ data differ slightly between this table and Table 1 due to different photometric methods used; the differences can be taken as indication of external uncertainties combined with the genuine variability.